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Selected presentations given at this symposium held at Aachen, West Germany, are discussed. Topics are: shock experiments, Mach reflection, and computational methods.


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# 16TH INTERNATIONAL SYMPOSIUM ON SHOCK TUBES AND WAVES

The sixteenth in the biennial series of International Symposia on Shock tubes and Waves was held in Aachen, West Germany. Since 1865 Aachen has been the home of the Rheinish-Westfälische Technische Hochschule (RWTH), currently attended by over 35,000 students, 80 percent of whom study science and engineering.

The symposium was attended by over 300 participants from nine countries, including China, Romania, Poland, Czechoslavakia, and the Soviet Union, which sent a sizable delegation. Ten invited lectures were presented in plenary sessions. In addition, 120 contributed papers selected from 166 abstracts by the organizing committee, chaired by Professor Hans Grönig of RWTH's Shock Wave Laboratory, were presented in three parallel sessions. I chose to attend those in the areas of my own research interests: shock structure and stability, detonations, and computational techniques.

## Shock Experiments

In the introductory Vielle invited lecture, Daniel Bershader of Stanford University, California, discussed compressible vortices produced experimentally by the interaction of planar shocks with an oblique airfoil. Each shock gives rise to a nearly circular vortex, which then breaks off and propagates almost uniformly following the shock that produced it. Bershader and his students have studied their interaction with a second airfoil downstream from the first, as a function of the parameters of both vortex and airfoil. Naturally enough, the primary application is to transonic flow over the blade tips of rotary-wing aircraft. Holographic interferography is used extensively for diagnostic purposes.

The vortices are anisentropic, with a rigidly rotating core and an external region in the form of a free vortex. The density profile is well described by a Lorentzian. The azimuthal velocity is typically of order 200 $ms^{-1}$; a weak but distinct temperature maximum ~325 K, apparently associated with viscous dissipation, appears where the internal and external regions join. Viscosity also plays an important role in the formation of the rigidly rotating core. Essentially everywhere else the flow is inviscid, as shown by simulations done using a body-fitted TVD code developed at NASA Ames by Helen Yee (1987), which yielded density profiles in excellent agreement with the holographic pycnograms.

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Another shock-tube experiment of interest was that of Kulkarny, et al., of TRW, presented by Willi Behrens. In this work very detailed measurements were made of the dust lofted or "scoured" from a layer in the bottom of a 17-inch shock tube, along with laser Doppler velocimeter measurements. Both fine (diameter ~7 μm) and coarse (~100 μm) dry, natural soils were used. Dust scouring is important because it plays a significant role in determining the dynamic pressures developed by blast waves from nuclear air- and surface bursts. Density profiles were recorded to 10 ms. The scalded velocities and the ratio of total to dust density both equalled $(y/\delta)^{0.7}$, where $\delta$ is the dust-layer thickness. This result confirms and extends the unpublished (but widely cited) results of Hartenbaum. Dust scouring rates were found to be approximately $m = 0.03\,\rho_e u_e$, where $\rho_e$ and $u_e$ are the air density and velocity outside the boundary layer. Results with uniform glass beads displayed more complicated behavior; they were picked up more readily, but the rates saturated at high values of $y$.

Martin Sommerfeld of Erlangen-Nürnberg University, West Germany, described a computational model of supersonic dusty flow. He used 4000-6000 macroparticles (parcels representing multiple dust particles) to trace the evolution of the dust components, and a finite-difference hydrocode to describe the air. The two components are coupled unconditionally at high Reynolds number, and by using standard Stokes drag coefficients for Re < 1000. It is of interest to note that the numerical treatment of the fluid component is essentially the same as the Piecewise Linear Method (PLM) developed by P. Colella and P. Woodward (1983a) of Lawrence Livermore National Laboratory (LLNL). This technique, along with the Piecewise Parabolic Method (PPM) (Colella and Woodward, 1983b) has been widely hailed as the state of the art in hydrocode techniques and is now extensively used in the US. It was developed during the past decade with support from the Defense Nuclear Agency (DNA). In an effort to avoid technology transfer to Soviet-bloc countries, DNA has interdicted distribution of the code overseas, even to DNA contractors in allied nations. It is a measure of the effectiveness of this policy that Sommerfeld was apparently able to code up a working version just using the published descriptions.

John Lee of McGill University, Montreal, Canada, gave an invited lecture on dust explosions. These were first encountered in connection with coal production, but have since been seen in the metallurgical and pharmaceutical industries, in grain and flour handling, and elsewhere. The approach of research in this area has

been overwhelmingly heuristic and practical, with the aim of determining explosive force and ignition sensitivity and developing preventive measures.

A characteristic of dust explosions is the very high radiation intensities they engender. The photographs Lee showed depicted bright orange and yellow flames. Indeed, there is a continuous transition from "dust combustion" to "dust explosion," and the difficulty in specifying a quantifiable reproducible boundary between the two is at the root of much of the uncertainty in the field. The principle measurables in dust explosion research are minimum ignition temperature, minimum dust concentration and maximum oxidant concentration for detonation, maximum rate of pressure rise, and maximum explosive pressure. Most of the results Lee presented involved the determination of these quantities.

Harold Mirels of the Aerospace Corporation, El Segundo, California, described the model he has been developing of the interaction between a moving shock wave and a thin, stationary layer of helium or heated air next to the shock tube wall. This problem arises out of attempts to understand the effects on blast waves of the prompt radiation from a nuclear airburst, which heats the surface soil and thence the air next to the surface in the vicinity of ground zero. As a consequence of the elevated sound speed in this layer, a precursor propagates ahead of the foot of the Mach stem. DNA has fielded experiments using helium to simulate the heated layer, and several computational groups have treated the problem, including those at the Naval Research Laboratory (NRL), the Naval Surface Weapons Center (NSWC), and S-Cubed/San Diego.

Mirels modeled the Mach stem with a planar shock wave. He studied the low-Mach-number limit, for which the precursor and other features appear steady in the incident shock frame. The precursor appears to be driven by a wall jet composed of shocked, unheated air, a tongue of which winds around and under the triple-point region, ending in a rollup. This geometry is quasi-one-dimensional and can be characterized by the shock Mach number and the ratio of sound speeds ahead of the shock. It follows that the locations of the various features and the boundaries between neighboring regions at the wall are determined to within one adjustable parameter, $k$, which models the ratio of vertical to horizontal flow. For the version of the theory in best agreement with experiment. Mirels calibrated $k$ against the results of the S-Cubed simulations (Schrayer and Wilkins, 1984) obtained with a version of the Hull code modified by the inclusion of flux-corrected transport (FCT). (He used these because only the S-Cubed workers gave him a printout containing all the numbers he wanted.)

The theory agrees qualitatively with the experimental data and, with the best choice of $k$, quantitively as well. Ludmila Gvozdeva of the Institute for High Temperatures, Moscow, was so interested in the paper that she taped it in its entirety. A. Kh. Mnatsakanyan, also of the Institute for High Temperature, described experimental and theoretical work on the propagation of planar shocks through one-dimensional regions of localized density or internal (e.g., vibrational) temperature inhomogeneities. An electric-arc-driven shock tube produced N-waves, which propagated through the "holes" and were diagnosed optically. The simulation was done using a back-and-forth piston motion to generate the N-waves; the holes were molded by smooth distributions of the fluid variables, satisfying pressure balance. A Lagrangian finite-difference scheme was employed. The interesting phenomenon here was that the N-waves first sped up, then slowed again in passing through the holes. Although deformed in the process, they returned to their original shapes with some residual loss of strength. The velocity changes agreed with predictions made using the Chester-Chisnell-Whitham (C-C-W) method.

## Mach Reflection

An entire session was devoted to nonideal or nonstandard Mach reflection phenomena. In an invited paper, T.V. Bazhenova, of the Soviet Union's Institute of High Temperatures, discussed planar shock diffraction around wedges with curves instead of sharp corners. She also discussed shock propagation in porous media (polyurethane foam). In common with most or all of the Soviet papers and in accord with the usual Soviet practice, this talk apparently contained only previously published results.

The second invited paper, given by K. Takayama of Sendai University, Japan, described shock interaction with bubbles, a topic relevant to studies of damage due to cavitation. The shocks were produced by underwater explosions of $AgN_3$ triggered by laser light. When a shock impinges on a bubble it produces a jet, giving rise to pronounced pressure spikes. Takayama also described Mach reflection from liquid surfaces obtained by filling a chamber at the end of a tilted shock tube with water, silicone oil, etc. When the air shock speed exceeded the speed of sound in the liquid, a shock or shocklike signal propagates into the latter. In the opposite limit the experiments exhibited effects of "precursor " waves due to shocks propagating through the sidewalls ahead of the gas shock waves. Next, Takayama discussed shock propagation over wedges and circular cylinders in dusty-gas shock tubes which can give rise to "clean" (dust free) regions due to the action of the vortex associated with the triple point. He concluded by noting that shock interferograms had recently been employed to diagnose the 20-percent pressure fluctuations developed by the exhaust pipe in a Japanese auto manfucturer's small internal combustion engine.

Following the invited papers, John Dewey of the University of Victoria, Canada, described a series of shock tube experiments carried out to measure the signal speed (flow speed plus sound speed) immediately behind

the point at which the shock reflects from a wedge. Two different experimental methods gave consistent results for wedge angles between 50° and 65°. The transition from regular to Mach reflection is a perennial focus of controversy; the apparent discrepancy between experiment and theory gives rise to the "Von Neumann paradox." The "sonic criterion" predicts that this transition takes place when the signal from the corner at the upstream (leading) edge of the wedge catches up with the incident shock. The measured signal agrees closely with this prediction; the sound speed calculated from inviscid two-wave theory d ›es not. Dewey argued that this stems from the failure to properly account for the viscous boundary layer.

Next was a paper by Gabi Ben-Dor of Ben-Gurion University, Beer-Sheva, Israel, who began by showing a shadowgraph taken in a double-Mach-reflection experiment, in which the slip stream (contact surface) attached to the first triple point suddenly broadened after a fraction of a centimeter, evidently as a result of the onset of turbulence arising from the shear across the surface. Using the Von Kármán equations for the growth of boundary layer thickness as a function of the displacement x, he calculated the position of an imaginary displaced slipstream. If the boundary condition is imposed at this position, calculations based on the Von Neumann three-wave theory yield excellent agreement with the experimental data for the angle at which the transition to Mach reflection takes place.

Later in the session, Z.A. Walenta of the Institute of Fundamental Technical Research, Warsaw, Poland, presented experimental results on Mach reflection in rarefied gases. His data indicated that the onset of reflection (regular and Mach) is displayed by ~100 times the collision mean free path. If the wedge corner is displaced by this amount (effectively increasing the triple-point opening angle), the geometry of the flow in the Mach-reflection case is accurately described by H. Hornung's asymptotic strong-shock theory (Hornung, 1986) even for work shocks.

Werner Heilig (Ernst-Mach Institute, Freiburg, West Germany) presented a modification of the Von Neumann theory for regular reflection. The new theory retains Snell's law, while replacing the second equation (which asserts that the flow behind the reflection point is turned parallel to the wall) with a fit to experimental measurements of the pressure jump across the reflected shock. Then three-shock theory applied to the resulting solution accurately reproduces the experimentally observed flow fields near the triple point. In this picture, single Mach reflection appears as a special case of double Mach reflection.

In another session, M. Kamegai of LLNL presented a numerical study of underwater shock waves reflecting from the air-water interface. These shock wave typically reflect as a rarefraction wave or a fan of such waves. Theoretical predictions derived from equation-of-state data agree with the simulation results only in the weak-shock limit. The paper was of interest chiefly for the computational method, which employed two codes in succession: a Lagrangian code for the explosion phase, followed by an Arbitrary Lagrangian Eulerian (ALE) code for the subsequent wave propagation and reflection. The latter treats air and water as a single fluid, whose thermodynamic properties are advected with the flow. Thus there is no boundary at which diffusive mixing can occur; the automatic rezoning which takes place when the Lagrangian zones become highly distorted apparently also introduces no mixing.

In an invited talk, Roy Henderson of the University of Sydney, Australia, presented a maverick theory of the transition to Mach reflection. His contention is that for shocks which are strong (supersonic flow downstream) and steady, the criterion for the transition is the Von Neumann flow-turning condition, rather than the sonic or detachment criterion (either inviscid or modified by the inclusion of viscous effects). In support of this position he presented his own experimental data on shock reflection, diffraction, and refraction (the "most general" phenomenon) and numerical results from the work of P. Colella and H.M. Glaz (1985). He further maintained that in the weak-shock limit Mach reflection does not actually occur (the reflected shock is replaced by a compression wave). In this limit the sonic criterion appears to apply.

There followed three contributed papers on shock focusing by reflection. The most important is to intracorporeal lithotropsy, i.e., the breaking up of gall- and kidney stones inside the human body by weak externally generated shocks brought to a focus at the location of the stone. Over 3000 patients have been treated in this manner in Aachen's medical school alone. The first two of these papers, of which Michio Nishida of Kyoto University was a coauthor, emphasized two-dimensional computational studies. Like Sommerfeld's work (above) they employed PLM. (I understand that Sommerfeld had just come back after spending a year at Kyoto, so perhaps Nishida is responsible for overcoming the PLM embargo.) The results were extremely impressive, especially when the experimental shadowgraphs were compared side-by-side with the numerical ones. (The latter were produced by contouring the Laplacian of the calculated density, presumably after some smoothing.) The third paper, entirely experimental, described joint Japanese-Australian studies of three-dimensional shock focusing using ellipsoidal reflectors.

## Computational Methods

The computational session featured mostly higher-order Godunov (HOG) methods, i.e., those in which upstreaming is accomplished by solving a Riemann problem locally using the discretized data from the previous time travel. B. Esser and B. Einfeldt, from two dif-

ferent departments of RWTH, apparently working in ignorance of one another's activity, talked about development of nearly identical codes. Both are developing real-gas Riemann solvers for use in HOG methods, particularly PLM, thereby generalizing the work of Colella and Glaz (1985). Esser's solver is extremely general but is not yet optimized. Einfeldt's is already implemented in a working hydrocode but is less general. Richard Hillier of Imperial College, London, presented calculations done using the HOG method of Ben-Artzi and Falcon (1984) of the diffraction of a planar shock around a 90° corner. With the best resolution available to him (about 29,000 zones) he obtained excellent agreement with Bazhenova's experimental results (Bazhenova, et al., 1984).

Finally, in perhaps the most impressive calculation of the session, Munz of the Karlsruhe Nuclear Research Center, West Germany, presented results on collapsing cylindrical shock waves obtained using a form of MUSCL (Van Leer, 1979). They were done in both Cartesian and cylindrical geometry, using up to 40,000 zones. Optimized for the Cyber 205, the code runs at 0.6 seconds/timestep on this grid (about 2 μsec/zone/timestep/coodinate sweep). He followed the evolution of perturbations with mode numbers up to $m = 16$, observing linear and then nonlinear instability during implosion, then stabilization and damping in the expansion phase.

The invited talk given by Harland Glaz of the University of Maryland (formerly of NSWC) was a tour de force. He began with a brief history and explanation of HOG methods. They grew out of the scheme devised by Godunov in the Soviet Union around 1960. The earliest version was highly dissipative, but the idea of using a Riemann solver to make sure that information only propagates along the characteristics caught on. In the middle 1960's J. Glimm used this as the basis for the Random Choice Method. A. Chorin adopted it for one-dimensional problems. In the late 1970's Van Leer developed MUSCL, a Lagrangian second-order Godunov algorithm. Beginning around 1980, Colella and Woodward devised PLM and PPM. Philip Roe in England and Ari Harten in Israel and at the Courant Institute (New York) developed "Total-Value-Diminishing" (TVD) algorithms. A. Harten and H. Yee have a version of the latter using something called vector splitting.

Most of these algorithms are explicit (although implicit TVD schemes have been devised, and hybrid techniques are possible). Most are timestep-split (coordinate-split), but this is not necessary in principle. Marsha Berger at the Courant Institute and Colella have developed an unsplit version, which they use in connection with an involved mesh-refinement scheme based on overlaying patches of fine zones on top of coarser grids. These developments have not been effortless. A vast number of person hours and a comparable number of Cray hours have been expended in the process.

Following this introduction, Glaz showed a long series of PLM and PPM results from shock-on-wedge calculations, mostly generated at Livermore or at NSWC in collaboration with Colella and W. Glowacki. All of the calculations, typically done on nonuniform meshes with $10^4$-$10^5$ zones, appear highly detailed. In many cases detailed comparison with interferograms taken from the corresponding experiment revealed contour-by-contour agreement.

Ideal-gas calculations with various Mach numbers, wedge angles, and values of $\gamma$, ranged from regular to triple Mach reflection. These last results are somewhat disquieting; they invariably exhibit a primary Mach stem that is strongly bowed (convex) in the forward direction, with the new triple point at the junction between the original Mach stem and the bend. Such structures have seldom, perhaps never, been observed experimentally. In subsequent discussion Glaz claimed the substantial bowing-out is observed for high-density (and low $\gamma$) gases like sulfur hexachloride or the Freons, or at Mach numbers $M > 20$-$30$. (The latter are impractical in most shock tubes because the windows blow out above $M \sim 15$.) Glaz did produce some experimental pictures that showed bowing-out resembling that calculated. Nevertheless, some explanation is still needed for the apparent discrepancy.

Another, less serious, discrepancy arises in connection with so-called terminal double Mach reflection. In this case the straight shock connecting the two triple points descends rapidly to the second one instead of being roughly parallel to the wedge surface or rising slightly, and the second triple point is observed to lie on the wedge surface. Earlier, Henderson (above) had showed some pictures of terminal double-Mach reflection taken in his shock tube. Glaz and his collaborators, in spite of considerable effort, have never succeeded in finding a combination of parameters for which the second triple point actually reaches the wall.

At elevated temperatures a real-gas equation of state is needed. This necessitates substantial modification of the Riemann solver, which in general becomes iterative (Colella and Glaz, 1985). Glaz showed a number of comparisons between calculations done using ideal and non-ideal versions of PLM. In most cases the differences were nearly imperceptible. The level of verisimilitude attained by the code appears to be so high, however, that only small incremental improvements are possible. In any case, the development of real-gas Riemann solvers involving vibrational and nonequilibrium states and chemistry shows that there is no bar in principle to using the method to study combustion, detonations, and other reactive flow problems.

Glaz showed a number of examples of height-of-burst phenomena (including both a chemical explosive and a nuclear example), demonstrating the capabilities of

the axisymmetric form of the code. When a high-sound-speed layer is introduced in front of the Mach stem, the usual precursor wave appears, driven by a supersonic jet of shocked unheated gas. This jet is unstable, and a veritable menagerie of kinks and vortices ("coherent structures") appears. Several strategies (massive over-refinement, nonuniform grids, high-resolution patches, etc.) have been employed to study this region. The detailed picture that results is probably the most impressive achievement of the method. Glaz concluded by discussing recent work and work in progress, including attempts to exceed the Courant limit locally without loss of stability.

The second invited paper of the day, given by Brad Sturtevant of California Institute of Technology, Pasadena, was almost equally interesting for me because of the close relation between it and the paper I was presenting. Sturtevant described a series of experiments on the breakup of gas bubbles under the influence of impinging shock waves. At first the bubbles deform impulsively; then, after the shock has passed, the flow "coasts," i.e., evolves ballistically. Sturtevant persisted in referring to this evolution as a Rayleigh-Taylor instability, although neither Rayleigh nor Taylor had anything to do with it, and in fact it is not really an instability. A somewhat better appellation is "Richtmyer-Meshkov" instability.

Until recently, most of the published work on this subject was done in the Soviet Union. When a shock wave deforms an interface, shear is set up and a Kelvin-Helmholtz instability develops. Its nonlinear evolution dominates the late-time history of the phenomenon. Regardless of whether the bubble density is less than or greater than that of the surrounding medium, a bulge eventually forms which grows secularly and evolves into a jet. In the final stage the bubble separates into two or more vortex rings. Sturtevant felt that to get more than one was somewhat surprising.

To conclude his talk Sturtevant showed a dramatic color video of a series of calculations (representing altogether 3500 hours of Cray time!) of shock-bubble interactions, done by Karl-Heinz Winkler and Paul Woodward at Los Alamos National Laboratory, using a version of PPM. The simulations accurately reproduced all the features observed experimentally, but showed far more detail than Sturtevant's optical diagnostics. (And according to Sturtevant, what can be seen on the high-resolution scope at Los Alamos is far superior to the video.) However, no shock tube experiment has ever come close to costing as much as that video. I had mixed feelings about it, since I presented Löhner and Picone's simulation of the same experiment in a contributed paper immediately following Sturtevant's talk. While not as spectacular as the Los Alamos video, their calculation required only 30 minutes of Cray time to run.

The strongest impression regarding computational advances I gained from the meeting is of the power of HOG methods and the leading headlong rush within the community to adopt them. In one form or another they were mentioned in 15-20 papers; the next leading contender, FCT, was mentioned about one-fourth as often. The results achieved using HOG methods are routinely well-resolved and apparently accurate (faithful to the physics of the problem). The other recent computational development in the field that has impressed me (I was of course familiar with it prior to attending the symposium) is Löhner's work at the Naval Research Laboratory on an unstructured-grid form of FCT (Löhner, 1987). The latter technique has the additional advantage of being able to conform closely to irregular external and internal boundaries. By virtue of the adaptability of the triangular mesh, it uses roughly an order of magnitude fewer nodes than a Cartesian grid for a typical shock-interaction problem, which may make it fully competitive with the HOG codes.

In my talk I emphasized the novelty of Löhner's FEM-FCT technique and the interpretation of the observed internal diffracted shock wave in analogy with the precursor wave in a high-sound-speed layer. This useful analogy became evident as a result of discussions I had had with Heinz Reichenbach and Werner Heilig when I visited Reichenbach's Ernst-Mach Institute for High-Speed Dynamics in Freiburg prior to the Symposium. Both there and at the RWTH Shock-Wave Laboratory I toured the experimental facilities and delivered a seminar on the "Stability of Self-Similar Spherical Detonations." In spite of my having arrived at an awkward time I was warmly received at both places and found these visits enjoyable and rewarding.

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